An Acoustic Communication and Navigation System for Shallow Water and Surf Zone Applications

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LONG-TERM GOALS

The long-term goals of this program include the development of a complete, integrated communications and navigation system capable of operating with many platforms in both very shallow water (VSW) and surf zone (SZ) conditions. For mine countermeasures (MCM) surveys, the payoff for the system is an accurate, coordinated search among multiple types of MCM survey vehicles with different sensors.

OBJECTIVES

The objectives of the program include the design, implementation and testing of a passive (*i.e.*, the users are listen-only) navigation system with a built-in acoustic communication capability. The system is specifically designed for use on small crawlers such as the Foster-Miller lemming or small autonomous underwater vehicles (AUVs) such as REMUS. In order to accommodate large numbers of AUVs within a relatively small area, a centralized beacon approach is used. Thus, the users within the net only listen, unlike long baseline approaches, which require each user to actively interrogate the network. The communication protocols that will support the system are both single and multi-user. This allows efficient, quasi-random access to the acoustic channel and provides low-rate data uplink for status information as well as higher-rate transmission of data generated in response to an actual mine detection.

APPROACH

The approach to the effort includes three main segments: measurement of channel effects in shallow water and the surf zone, design of signals suitable for use under those conditions, and test and evaluation of the system to determine its performance and throughput. Further details on our approach are included in the 1999 report. Here we focus on FY2000 results.

WORK COMPLETED

Utility-Modem Communications Development. During the first year of the program, coding and signaling methods were developed and tested. Based on the results of these tests, a set of communication signals with data rates spanning 60 to 5000 bps were programmed into the Utility Modem. These signals were used to transmit AUV data from the REMUS vehicle during AUV Fest 1999 and were also tested as part of the Modem Fest component to that experiment. The results of these tests were evaluated and a second iteration performed to increase the data rate by better matching the error-correction coding to the observed error rates.

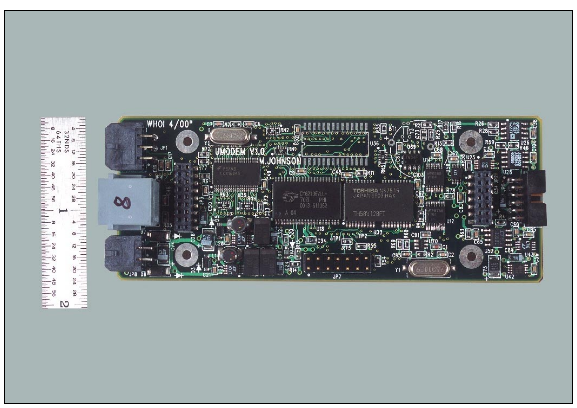
The resulting data rates for the signals are now approximately 300 to 6000 bps using a 5000 Hz bandwidth. These signals were used in June in Florida and also tested near Woods Hole.

Active and Passive Navigation. The navigation portion of the program includes both traditional, active long-baseline navigation and a means for many vehicles to listen to broadcasts from fixed nodes and determine their position without any active transmission. This past year the mathematical formalism for both methods were developed and validated in Matlab, then coded into C for use on the Utility Modem. The two modes of operation are similar and use a least-squares solution to determine position in a 2-D plane. The passive navigation solution utilizes an iterative refinement step to improve the accuracy of the least-square solution. Error maps for different geometries and signal-to-noise ratios have been generated as an aid to determining the best layout for grids with different numbers of nodes.

Utility-Modem Integration into the REMUS Advanced Development Model (ADM) Vehicle. During the first year the UAM was installed in an older model REMUS and operated during AUV Fest in 1999 (described in more detail below). This year the modem was integrated with the Advanced Development Model REMUS and operated during the June Fleet Battlelab Experiment (FBE-H) Rehearsal in Florida. The integrated system includes a transducer assembly designed by the REMUS development team, which adds the 15 kHz projector/receiver to the nose-cone of the vehicle.

Utility-Modem Installation and Test with the Foster-Miller Crawler. During the June FBE-H testing in Florida, a Foster-Miller crawler was outfitted with a Utility Modem and used for very shallow water testing. Results from this test are described on the next page.

Micro-Modem Hardware Development. The micro-modem hardware was completed this year. It is based on a prototype used for a solid-state recorder, includes a 100 MIP fixed-point TI processor, and has the capability to operate at different clock rates to minimize power consumption. A photo of the micro-modem main board is shown below.



Multi-User Frequency-Hop FSK Interoperability Standard. The multi-user frequency-hop standard to support inter-operable acoustic communication in shallow water was developed and documented this year. The results of the testing are described in more detail below.

Spread-Spectrum Receiver Design. Additional work on direct-sequence spread-spectrum communications was also performed this year. A new receiver, which utilizes a hypothesized data symbol for chip-rate adaptation in the decision feedback equalizer, was developed. The receiver was evaluated on simulations and experimental data and is described completely in [2].

Transducer Design, Construction and Testing. Two new transducer designs have been developed and tested. Based on bandwidth, beamwidth and power concerns, a design for a ceramic ring was developed and procured. The new transducers have been used on both the Foster-Miller crawler and on the fixed nodes. In addition, the ceramic is used in the custom-made nose transducer on REMUS.

RESULTS

AUV and Modem Fest 1999. This test was held in November 1999 in Gulfport, MI. The acoustic communications testing with both REMUS and during ship-to-ship operations was documented completely in [1] and is not included here.

FBE-H Rehearsal. During the FBE-H Rehearsal held at SFOMC during June 5-17, a number of different acoustic communications and navigation tests were performed using REMUS, a Foster-Miller crawler, and two research vessels. The communication and navigation infrastructure was provided by two Utility Acoustic Modems and radio-equipped buoys borrowed from the ONR MURI program and installed approximately 1800 meters from the beach in 15 meter deep water. The primary tests included: (1) REMUS acoustic communications uplink in shallow water and very shallow water; (2) Integrated acoustic communications and navigation; (3) Foster-Miller crawler bi-directional acoustic communications in the surf zone; and (4) Acoustic communication interoperability.

1. *REMUS Acoustic Communications.* One REMUS vehicle (ADM class) was equipped with a Utility Acoustic Modem with bi-directional capability. The modem has the capability to transmit and receive at 300 to 6000 bits per second, but it was utilized for low-rate status messages and thus, only the lowest bit rate was transmitted throughout the test. The acoustic modem was used to upload status messages on most missions run with this vehicle. Performance was very good in both the shallow and very shallow test areas where the range to the REMUS was generally less than 1500 meters. During the second week of testing when REMUS was operating in the northern area the range of the acoustic link was increased to as high as 2500 meters. Performance varied with conditions, but communications were often successful even when REMUS was operating in 3-4 m water depths.

2. *Integrated Acoustic Communications and Navigation.* On June 15 the R/V Oceaneer was used to test the integrated acoustic communications and navigation system, which employs at least two fixed nodes and one client. This version of the system provides bi-directional communication and LBL navigation in one frequency band by time-division multiplexing. The master buoy controls the function at each time slice, which is allocated to one of the following functions: (1) uplink from any one client to the master node, (2) downlink to any client or group from the master node, (3) peer-to-peer communication between any two units, fixed or mobile, and (4) LBL navigation by any mobile client. All of the above functions were tested during this experiment. Each cycle is initiated by the master buoy, which sends out a short data packet with a command indicating the allocation of the current slot. During this test the primary function was to allow the client to perform an active LBL cycle. In this mode the two buoys respond with individual coded sequences. The client determines the travel-time to each buoy and then computes its position based on the known buoy locations. After an LBL cycle the master may allocate a time slot to data upload from the client to retrieve the current position and status.

   At the start of the test, the R/V Oceaneer was positioned near the South buoy. The vessel drifted northwest through the test area, with the modem computing navigation fixes and uploading data back to the buoys. After the vessel reached the top of the box, it was repositioned near the center and a second test segment performed. Since the buoy locations were not precisely known (measured from a vessel nearby without differential GPS), reconciling the ship's track (also not based on differential GPS) with the modem-computed navigation locations required some adjustment of the baseline. However, when this is done there is excellent agreement between the two. Additional testing is still needed to validate system navigational accuracy. This will be done under more controlled conditions.

3. *Foster-Miller Crawler Communications Testing in the Surf Zone*. Several tests were performed with a Utility Acoustic modem installed in one of the larger Foster-Miller crawlers. The tests were performed from the State Park beach, about 1900 meters from the buoys. The low-rate signal was used for all of these tests. While the buoys were not placed with the intention of using them to communicate acoustically with the crawlers in the surf zone, the link was often reliable, though sometimes intermittent, depending on the position of the crawler (depth and north-south location). During the June 13 test, the waves were approximately 0.6 meters high and when the crawler was located in just 1.5-meter deep water, the signal was received on both buoys.

   For the uplink tests the performance depended upon location of the crawler. For several 30-minute periods the uplink from the SZ to the buoys 1 mile away was quite reliable. However, moving the crawler just 50 meters north or south was often enough to shut down the link. The reason for this is almost certainly the outer reef, which shoals to about a 4-meter depth at a point 400 meters offshore. The structure of the reef varies, and depending on the position of the crawler, the acoustic line of sight to the buoys may be occluded by the reef. However, given the range and conditions, the results were surprisingly good. During one test period the buoys received data while the crawler was in 1.5 meters of water with 0.6 meter breaking waves. The bi-directional test had similar results. When the crawler was positioned just beyond the line of breaking waves, the downlink was often consistent. However, at certain locations along a north-south line parallel to the beach, the link would be unavailable.

4. *Interoperability Testing*. The objective of the interoperability test was to demonstrate that acoustic modems from different organizations could be used together. This is an on-going effort with the physical-layer definitions being developed at Woods Hole [3]. The tests included three systems: (1) the FAU modem with the complete physical layer including packetization, error-correction and frequency-hop modulation; (2) the Benthos modem pre-programmed with a table of frequencies representing a standard test packet; and (3) the WHOI Utility Acoustic Modem operating as a real-time receiver. While two different rates and hopping code sets are defined, only one was tested: 160 symbol per second (80 bits per second after ECC). The Benthos modem utilized Band A (7.6-11.8 kHz), while the FAU modem used Band C (23-27.2 kHz). The at-sea interoperability demonstration was performed using two vessels. The transmit vessel drifted, transmitting from each different acoustic modem in turn. Two different tests were performed; one toward shore, the other along shore.

   Two different drift tests toward shore were performed with the Benthos modem. Ranges of 1400 and 1750 meters were readily achieved. During one test the vessel drifted over the outer reef whereupon the signal level was reduced slightly. However, the signal-to-noise ratio (SNR) increased and then held approximately constant out to the maximum range of 1750 meters. Overall, the reliability was high (better than 90% packet success rate), though the packet success rate began to drop as the source vessel entered shallow water at approximately 1400 meters. During along-shore testing in Band A, the link worked very well at 2.4 km and began to have reduced performance at 3.5 to 4 km as the SNR dropped and additional signal fading was experienced. Similar tests were performed with the

FAU modem in Band C. The drift tests into shallow water also offered very good performance, and the along-shore tests were very reliable at the 2-3 km range.

Channel Characterization and Modeling in VSW and SZ. The WHOI work in channel characterization this year consisted of three primary efforts. These were planning and participating in the SZATE experiment, planning, conducting and analyzing data from a very shallow water experiment, and propagation modeling to investigate the attenuation effects of bubble clouds that partially block the acoustic channel.

The SZATE experiment this year was conceived of and planned to provide consistent long-term data regarding the outage and channel fluctuation characteristics of the surf zone channel. The experiment was led by Dr. Grant Deane at SIO and consisted of acoustic channel and environmental measurements. The acoustic channel measurements consisted of the repeated transmission of an 18-minute suite of signals once every 2 hours over a two-month period. In the same time frame, surface wave and bubble cloud measurements were recorded. During a one-week period more extensive environmental measurements were taken as part of a complementary effort by Dr. Deane and Dr. David Farmer of IOS. This data will enable a more complete characterization of the surf zone acoustic channel than was possible with the data from the 1999 Near Shore Acoustic Experiment (NSANE). An extensive analysis of the acoustic data and correlation with the environmental measurements is planned for FY01.

In May, an 8-day very shallow water acoustic channel characterization experiment was conducted off the Trunk River beach in Falmouth, MA. This experiment represented the first deployment of equipment developed under the DURIP grant to Dr. Preisig for the development of a High Frequency Acoustic Testbed. The experiment configuration consisted of a single transmitter programmed to transmit an approximately 24 second suite of acoustic signals once every 4 minutes. Two receiving stations were set up at different locations corresponding to slight and moderate upslope propagation paths from the transmitter. Simultaneous water temperature, current, and hydrostatic pressure measurement were taken at the experimental site as well as wind speed measurements. These measurements will allow characteristics of the acoustic channel to be correlated with tide, current, and surface wave conditions.

Finally, Dr. Preisig and graduate student James Partan performed an analysis of the attenuation in the surf zone acoustic channel when a bubble cloud blocks only the upper portion of the channel. This analysis was conducted using the OASES acoustic model, which was modified by Mr. Partan to accommodate upslope propagation. The model was run over a range of frequencies to allow for the computation of the channel impulse response as a function of receiver position and bubble cloud penetration depth. The scenario that yielded the most interesting results consists of an offshore source, a near shore receiver, and a bubble cloud just offshore of the receiver location. The results indicate that even when the bubble cloud penetrates only partially into the water column, the signal at all depths at the receiver location is attenuated. This attenuation includes the direct arrival even though no bubble cloud is in the direct line of sight between the source and receiver. A further analysis of this situation and the implications for communications system performance as well as confirmation using experimental data from the SZATE experiment will be conducted in FY01.

RELATED PROJECTS

Scripps Institute of Oceanography: Acoustic channel characterization in the surf zone. Institute of Ocean Sciences: Surf-zone measurement and analysis.

REFERENCES

[1] L. Freitag, M. Grund, S. Singh and M. Johnson, 2000. Acoustic communication in very shallow water: Results from the 1999 AUV Fest, *Proc. Oceans 2000*, Providence, RI. September.

[2] M. Stojanovic and L. Freitag, 2000. Hypothesis feedback equalization for direct-sequence spread-spectrum underwater communications, *Proc. Oceans 2000*, Providence, RI. September.

[3] Multi-User Frequency-Hopping Underwater Acoustic Communication Protocol, ver. 1.02, May 25, 2000, Woods Hole Oceanographic Institution, ftp://ael.whoi.edu/pub/fhfsk.pdf.